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Visible Laser Diodes: Properties of Blue Laser Diodes

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17.1 Introduction

The fact that the demonstrations of red and infrared laser diodes (LDs) in the early 1960s were not quickly followed by the development of similar shorter wavelength devices was not due to a lack of desirability and commercial attractiveness but rather due to the difficult nature of the wide bandgap semiconductors. Despite early work on II–VI compounds, GaN and ZnO, the technology and quality of epitaxial structures composed from these materials lagged far behind that of narrower gap materials such as GaAs. High-brightness blue light-emitting diodes (LEDs) and lasers were not developed until the 1990s and followed major advances in the fabrication of group III-nitride (AlGaN) structures. This chapter presents an outline of these developments and then proceeds to a description of the current status and performance of GaN-based blue LDs. The extension of the lasing wavelength in GaN-based lasers to both shorter (UV) and longer (blue/green) wavelengths is described along with the competing technologies: namely ZnO-based structures and frequency doubled systems for the blue and II–VI semiconductor structures for the green/yellow spectral region.

Note that the performance, range, and applications of short-wavelength LDs (and LEDs) are still improving rapidly with time, and this chapter represents the situation in spring 2002. For a deeper understanding of the development and properties of blue LEDs and lasers, the reader is directed to several books [1,2] and conference proceedings [3,4].

17.2 The Development of Blue LEDs and Laser Diodes

17.2.1 InGaN-Based LEDs

The commercialization of the first short-wavelength LDs (violet, 400–410nm emission) by the Nichia Corporation in February 1999 was the culmination of a dramatic series of research successes. The work within Nichia, under the leadership of Shuji Nakamura, spanned almost a decade and has been well documented (e.g. [1]). It included demonstrations of ultrabright UV, blue, green, and amber InGaN/GaN LEDs and rapid progress in improving the operating characteristics and longevity of violet LDs.
These achievements built on notable research successes by Akasaki and others in overcoming the main problems that had thwarted the development of GaN-based devices following the demonstration of metal–insulator–semiconductor LEDs in the 1970s [5]. The two main problems were the poor crystalline quality of GaN and the lack of a viable route to p-type material. High-quality GaN crystalline films were first grown in the late 1980s by metal–organic vapour-phase epitaxy (MOVPE) using low-temperature-grown buffer layers of AlN [6] or GaN [1]. These layers helped to isolate a region of high-quality GaN from the nitride–substrate interface, where lattice and thermal mismatches generate severe dislocations and defects. Nakamura made a further significant improvement in GaN epitaxy through the development of a novel two-flow MOVPE reactor [1]. The quality of MOVPE-grown III-nitrides has continued to improve at a rapid rate. As discussed later, additional dramatic reductions in dislocation densities were essential for laser development and were achieved using lateral epitaxial overgrowth techniques. The doping problem was also solved by Akasaki’s group who produced p-type GaN by irradiating Mg:GaN with low-energy electrons and fabricated the first electroluminescent GaN pn diode GaN [7]. Nakamura subsequently showed that thermal annealing in a nitrogen ambient was a better method of p-doping, with advantages including speed, reliability, and homogeneous conversion of the full depth of a layer [1]. By early 1991, Nakamura was fabricating homojunction GaN LEDs emitting 430-nm blue light with output powers and external quantum efficiencies approximately ten times greater than commercial SiC blue LEDs at that time [8]. The light emission originated from an impurity transition related to the magnesium dopant within the p-GaN and rapid progress was made on changing to the use of band-edge emissions in InGaN. The Nichia Corporation was the first to succeed in the commercial production of high-brightness blue LEDs, starting in November 1993. Toyoda Gosei Co., Ltd also pioneered similar devices, starting commercial production in October 1995.

The performance of GaN-based LEDs improved rapidly with the incorporation and improvement of InGaN quantum wells in the active region. The main features of GaN-based LEDs on sapphire substrates are as follows: following the deposition of GaN nucleation layers, several micrometres of n-type Si-doped GaN are grown. Next comes the active region incorporating InGaN quantum wells (typically 1–4 nm) with either GaN or low-InN fraction InGaN barriers and, finally, a p-type GaN layer. The Mg dopants must be activated and are contacted with Ni/Au. For LEDs on sapphire substrates, the underlying n-type material is exposed by etching through the top layers and contacted using Ti/Al.

Nichia has LEDs incorporating multiple InGaN quantum wells with room-temperature external quantum efficiencies of approximately 20% in the blue (11 mW with a forward current of 20 mA, 50 A cm$^{-2}$) and green (8 mW, current as before) [9]. Figure 17.1 plots the external quantum efficiency against LED emission wavelength, showing the fall-off either side of the blue/green region. Measurements as a function of temperature for a 400-nm emitter indicate a considerable (more than double) improvement in efficiency on cooling to $\sim$100 K [9]. These LEDs contain remarkably high densities of dislocations threading through the active region ($\sim$10$^{10}$ cm$^{-2}$)

[10]. Comparisons with LEDs fabricated on laterally overgrown GaN with considerably reduced dislocation densities (<10$^{10}$ cm$^{-2}$) show virtually no improvement for blue LEDs [11] and only a slight improvement (~25%) for UV LEDs [9,12]. Such results are indicative of the origin of the InGaN luminescence, which results from radiative recombination within localizing InN-rich nanometre-scale regions [13–15]. This spontaneous extreme localization isolates the carrier recombination from the non-radiative recombination centres at the dislocations and leads to a surprising independence of luminescence efficiency from dislocation density. The low InN mole fraction in UV InGaN LEDs does allow for some improvement due to the limited number and depth of the localized states.

Several other groups soon followed Nichia and Toyoda Gosei in the fabrication of high-brightness blue/green LEDs, including a number of variations on the general scheme outlined earlier. Use of conducting substrates, such as 6H-SiC, offers a number of advantages: principally, the use of a vertical geometry with a back contact. Different approaches to metal–organic chemical vapor deposition (MOCVD) growth reactors have been successfully employed, and InGaN LEDs have also been fabricated using molecular beam epitaxy, although not of commercial quality.

Currently (spring 2002), the best InGaN LEDs emit 30 lumen W$^{-1}$, but the performance continues to improve at a rate indicating that over 100 lumen W$^{-1}$ is achievable (this is to be compared with 15 lumen W$^{-1}$ for conventional incandescents and 50 lumen W$^{-1}$ for conventional fluorescents). One of the leaders in the development of high-power LEDs, Lumileds Lighting, has advanced flip-chip Luxeon devices showing record external quantum efficiencies of ~30% and optical powers in excess of 1 W (at 425 nm) in a $2 \times 2$ configuration of LEDs [16,17]. CREE Inc. has high-brightness ‘Xbright’ LEDs on SiC emitting at 470, 505 (11 mW) and 525 nm (9 mW) [18]. White GaN-based LEDs can also be fabricated using a number of routes. Devices emitting ~20 lumen W$^{-1}$ are available.
using a blue LED coated with a yellow phosphor, which partially transmits the blue light. The impressive performance of III-nitride LEDs is exemplified by the demonstration of headlights using white Lumileds Luxeon LEDs on a concept car unveiled at the 2002 Geneva Motor Show.

17.2.2 The First GaN-Based Laser Diodes

The bright InGaN/GaN LEDs produced by Nakamura’s MOCVD process and with p-type material resulting from thermal activation of Mg donors were the forerunners of the violet LDs. However, additional problems would have to be overcome to achieve reliable lasers. The fabrication of mirrors for a diode laser’s optical cavity is generally achieved by cleaving, which is not practical for the c-face sapphire substrates used for InGaN LEDs. Early InGaN lasers contained relatively rough mirror facets created by reactive ion etching [19]. Shortly afterward, Nakamura also demonstrated InGaN lasers on a-face (1120) sapphire substrates, where mirror facets could be formed by cleaving, although no reduction in threshold current was achieved [20].

The implementation of two additional features was significant for the extension of the laser lifetime and a reduction in the operating voltage. First was the inclusion of modulation-doped strained layer superlattice (MDSLS) cladding layers above and below the active region of the lasers. These GaN/AlGaN MDSLSs reduced cracking within the laser structure, improved optical confinement and lowered the operating voltage. The second was the implementation of lateral overgrowth on patterned silica substrates [21,22]. Stripes of silica, typically 4 µm wide and 12 µm apart, are deposited on a GaN surface prior to growth of a thick GaN layer. Above the mask, the GaN grows laterally and soon coalesces to form a flat surface with, most importantly, approximately 10^4 fewer dislocations cm^{-2} in the regions above the silica stripes. In simple terms, the silica mask has almost eradicated the memory of the GaN/substrate interface for these regions. The structure of one of these layer diodes is represented schematically in Figure 17.2. Further improvement of the lasers was achieved by removing the sapphire substrate from beneath several micrometres of overgrown GaN to create ‘GaN substrates’, which are easily cleaved and have the extra benefit of higher thermal conductivity [23,24].

The first reports of violet LD operation at room temperature under pulsed conditions [19] and then with continuous-wave (cw) operation [25] came from Nakamura in 1996. Using the steps previously described, the lasing lifetime was improved dramatically over a short period of time; with 30h in December 1996, 300h in May 1997 and accelerated lifetime tests indicating achievement of the ‘magical’ 10 000h lifetime in December 1997 [22]. The dramatic progress made by Nakamura in the late 1990s clearly shows the importance of minimizing dislocations for increasing the lasing lifetime. The degradation of InGaN LDs is also linked to the generation of heat within the p-cladding and contact layers, and there is a report suggesting a contribution of catastrophic optical damage to the failure mechanism [26].

17.2.3 The Structure and Performance of State-of-the-Art GaN-Based LDs

Following the previously described development, the Nichia Corporation proceeded to commercialize violet (~405 nm)-emitting GaN LDs with ~5 mW output in February 1999. Subsequently higher power (30 mW) versions (see Section 6.2.4) and extended wavelength (450 nm) LDs (see Section 6.2.5) were added to their product range.

Following Nichia’s lead, violet GaN-based lasers have been demonstrated by a growing list of other companies and universities, with early players including Toyoda Gosei, University College of Santa Barbara (UCSB), CREE Inc., Samsung and Xerox. These devices share a number of similarities—they all employ MOCVD crystal growth, with some approach to a reduction in threshold density (lateral growth, low-temperature interlayers, etc.); they are grown p-side up due to the relative difficulty in doping and require some approach to lateral current spreading within the p-layer. Differences between them include the use of a variety of substrates, with

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**FIGURE 17.2** Schematic diagram of the layer structure of one of the early ELOG GaN-based laser diodes from the Nichia Corporation. (From Ref. [22], reproduced with permission from the American Institute of Physics.)
the most notable variations being SiC (e.g. CREE Inc.), bulk GaN crystals (UNIPRESS [27]) or conductive ‘free-standing GaN’ (e.g. NEC [28]), which all allow use of a back-side contact. Note that Nakamura has reported lasing on a variety of substrates (including a-face sapphire [20], MgAl2O4 [29] and ‘free-standing GaN’ [23]). There are a number of variations in the lateral overgrowth technique for which a range of names and acronyms exist—ELOG, lateral epitaxial overgrowth (LEO), pendeoepitaxy™ [30], facet-induced epitaxial lateral overgrowth (FIELO) [28], lateral overgrowth from trenches (LOFT).

The structure and performance of the Nichia devices will now be summarized. Operating specifications and illustrative figures for Nichia’s devices are available on the company’s website [31]. All of their devices are based on a similar epitaxial layer structure, which can be generalized as follows. Starting with the reduced-defect-density GaN layer, a thick n-type GaN (or low-Al AlGaN) layer is followed by an n-type MDSLS, then an undoped GaN (or low-InN InGaN) layer containing InGaN quantum wells, then a p-type MDSLS layer, and finally, a thin p-type GaN layer. A more detailed layer structure reported for lasers [9] is represented schematically in Figure 17.3. These layers are deposited on a low-defect density GaN layer produced by a lateral overgrowth of GaN. Nichia has detailed the fabrication of LDs by ELOG on sapphire and also ‘ELOG on GaN’ [32]. The ELOG on sapphire utilizes 100nm thick SiO2 masks on ~2.5 µm of GaN. The masks are patterned into 8 µm stripe windows with 20 µm periodicity. Approximately 15 µm of GaN is then grown, giving a flat surface with very low defect density above the SiO2 stripes and a so-called ELOG substrate. A thick (200 µm) layer of GaN is deposited on this, using hydride vapor phase epitaxy (HVPE) with a high growth rate of 40 µm h⁻¹. The sapphire substrate, ELOG GaN and some HVPE GaN were then removed by polishing to obtain a free-standing GaN substrate. LDs are fabricated using the low-defect-density regions above the silica stripes. For the ‘ELOG on GaN’ substrates, the ELOG process is repeated to give a further reduction in the defect density. The dark spot density is reduced to 1 x 10⁶ cm⁻² for ELOG on sapphire and 7 x 10⁴ cm⁻² for ‘ELOG on GaN’. The n-InGaN serves to counteract the build-up of strain and prevents crack formation within the structure. The MDSLSs act as cladding layers to confine carriers and also serve to maintain crystal quality and reduce operating voltage.

The LDs have a ridge geometry (typically 2.5 x 650 µm). In Nichia’s case, a ZrO2 coating is used to define the ridge by refractive index confinement of the laser beam [9]. For LDs fabricated on ‘ELOG on GaN’ substrates, the facets are formed by cleaving, while for ELOG on sapphire, the facets are formed by reactive ion etching. Coating the facets, for example with TiO2/SiO2 multilayers, enhances device performance. Ni/Au is used for the p-contact and Ti/Al for the n-contact.

The laser emission wavelength is tuned mainly by control of the InN fraction within the wells, with a lesser effect from the width of the wells (see Ref. [33]). An optimization process for violet LDs resulted in a preferred well width of 2.5 nm, with wider wells resulting in increasing forward leakage currents and rising threshold current. With the choice of 2.5 nm well and 4 nm barrier layers, a second optimization showed a minimum threshold current for two wells (also a peak in emission wavelength) [32].

For the 405 nm, 5 mW LD, the quoted performance parameters are operating voltage (4.5 ± 1.0) V, operating current (50 ± 20) mA, and slope efficiency 0.7 W A⁻¹. The beam divergence (FWHM) is 10° and 28° for directions perpendicular and parallel to the growth direction. The LD spectrum reproduced in Figures 17.4 and 17.5 shows the output optical power plotted against forward current. The operating temperature is quoted as −10°C to 60°C, and Figure 17.6 plots the dependence of the peak wavelength on case temperature.

CREE Inc. have been developing blue/violet GaN lasers using SiC substrates and in February 2002 announced that their 405-nm, 3-mW blue LDs exhibited a projected lifetime exceeding 10 000 h at room temperature.

| 15 nm p-type GaN : Mg |
| 100 period Al0.1Ga0.9N:Si/ GaN:Mg MDSLS (500 nm) |
| 150 nm undoped GaN |
| 10 nm p-type Al0.3Ga0.7N : Mg |
| 2x 2.5nm In0.2Ga0.8N wells with 4nm In0.05Ga0.95N barriers . |
| 50 nm In0.05Ga0.95N : Si |
| 100 nm undoped GaN |
| 200 period Al0.1Ga0.9N:Si MDSLS (1000 nm) |
| 100 nm n-type In0.1Ga0.9N:Si |
| 5000 nm n-type Al0.1Ga0.9N:Si |

**FIGURE 17.3** Schematic diagram of the layer structure of GaN-based LDs from the Nichia Corporation.

**FIGURE 17.4** Lasing spectrum for the Nichia Corporation’s 5-mW diode. (Copyright Nichia Corporation [31].)
All the demonstrations of laser action in the III-nitrides feature efforts to reduce the number of dislocations resulting from the lack of an ideal substrate material. As described earlier, high-performance LDs have been fabricated using free-standing GaN substrates produced by the removal of an alien substrate (usually sapphire) following growth of a thick low-defect-density GaN layer. The availability of high-quality large crystals of bulk GaN promises dislocation densities that are orders of magnitude lower than in any other GaN and, consequently, a possible significant improvement in laser performance. However, the growth of bulk crystals of GaN is an immense challenge, due to the extremely high melting point (~2500°C) and equilibrium pressure at melting (~45000 atm!). The team at the High Pressure Research Centre, Polish Academy of Sciences (UNIPRESS) is alone in producing such crystals and has demonstrated a blue LD fabricated by MOCVD on a substrate cut from a GaN crystal [27]. The laser is a separate confinement heterostructure device containing five InGaN quantum wells. Dislocation densities in the n-type-conducting substrates are as low as 10–100 cm⁻², and fully strained MOCVD structures can be grown with no evidence for the formation of additional dislocations. Pulsed operation of the first laser at ~40°C showed a threshold at 1.7 A. The preparation of the bulk GaN substrates is clearly a highly technical challenge, but the rewards for overcoming it are similarly great. This is evidenced by reports of large improvements in performance of lasers grown at the Nichia Corporation in 1999 when Nakamura was provided with a small number of Polish bulk substrates (~10 increase in lifetime, ×2 increase in power over corresponding devices on sapphire) [27]. A number of alternative routes to ‘bulk-like’ GaN are actively being researched and show promise for the future.

17.2.4 Advancing GaN-Based LDs to Higher Power

The first commercial violet LDs had an output power of 5 mW, but for some major applications, e.g. DVD writers, higher power and longer lifetimes are necessary. (In February 2002, nine companies jointly announced the establishment of the basic specifications for a next-generation optical disc dubbed the ‘Blu-ray Disk’, designed for the recording, rewriting and playback of 27 Gbits of data on a single-sided single-layer CD/DVD size disc using a 405-nm blue-violet laser.) For optical disc writers, laser powers of 30 mW or above are required, and further increases in power are necessary for other applications, including laser-based display technologies, printing and certain medical applications. Additional desirable characteristics for high-power LDs include low operating voltage, the elimination of ‘kinks’ in the $L–I$ curves, improved far-field patterns by reduction of the aspect ratio of the emitting region, low noise, long life, etc.

The Nichia Corporation has improved the reliability of their high-power LDs by use of free-standing GaNs and has commercially available 30 mW lasers. These higher power ~408 nm devices have the same operating voltage (4.5 V) as their commercial 5 mW devices, and the typical operating current is only slightly higher, at 70 mA. Plots of the forward voltage and output power against forward current are shown in Figures 17.7 and 17.8. The slope efficiency has increased to 1.2 W A⁻¹, and the lateral spread (FWHM) decreased to 8° and 23° for directions perpendicular and parallel to the epitaxial growth direction (Figure 17.9). Results for 55 mW lasers at 60°C show lifetimes (defined as a 50% increase in current) exceeding 4000h for devices with both cleaved and etched facets, although productivity is improved by the latter.

NEC have developed high-power (>30 mW) devices using a ridge by a selective regrowth (RiS-) LD structure [34,35] on a low-dislocation laterally grown GaN (FIELO) [28], as
shown schematically in Figure 17.10. The RiS-LD initially suffered from internal losses caused by light absorption in the region of the regrowth boundary for the upper ridge, but performance has been improved by reducing the internal loss to as low as 26 cm\(^{-1}\). The main source of loss was identified as Si contamination at the regrowth boundary, the effect of which was minimized by shifting the optical field deeper into the structure using a thick low-Al content n-AlGaN cladding layer. The result was superior laser performance with a threshold current as low as 10 mA (\(J_\text{th} = 1.6 \text{ kA cm}^{-2}\)) with highly reflective-coated facets, as shown in Figure 17.11. The large differential gain and suppressed non-radiative recombination in these structures may be associated with the lack of a dry etching step in the fabrication process. An impressively low aspect ratio, 2.0, is achieved in the 30 mW lasers also benefiting from the extension of the optical mode vertically in the lower cladding layer [35].

Extremely impressive progress in high-power GaN-based lasers has been reported by Sony [36–38]. They have developed blue LDs emitting in excess of 100 mW and demonstrated a 4.2 W LD array consisting of 44 individual lasers (11 laser chips each with four monolithically integrated laser stripes). Deviation between the individual emitters is the key limitation here, but the power performance is impressive with a wall-plug efficiency approaching 10%. The 1 W cw lifetime of these laser arrays exceeded 1000 h at the time of writing. Figure 17.12 reproduces the \(L–I\) and \(V–I\) characteristics and lifetime data as presented at the ISBLLED2002 symposium in March 2002 [38]. It is noteworthy that the power consumption of an individual 100 mW blue laser (>20% wall-plug efficiency) is less than half that of an equivalent red LD. The Sony lasers use a licensed lateral overgrowth technique, based on pendeo-epitaxy [30], to reduce the dislocation density. ‘Kink-free’ \(L–I\) curves have been demonstrated for powers in excess of 100 mW with lateral beam spreads of 8\(°\) and lifetimes (defined by a 20% increase in operating current) in excess of 15 000 h. The kinks are associated with an increase in higher transverse modes, whose suppression is discussed in Section 6.2.6.

Improving the laser output aspect ratio by increasing the angular spread parallel to the layers (\(\theta_\parallel\)) will lead to the kinks discussed earlier, and thus, any improvement in the far-field pattern can preferably be achieved by reducing the angular spread along the growth direction (\(\theta_\perp\)). Raising the thickness of the guiding layer is associated with an increased threshold current (due to less confinement), and so the reduction of \(\theta_\parallel\) has been achieved by setting the active layer back from the p-AlGaN using an undoped spacer layer. An aspect ratio of
2.3 has been reported with no degradation in threshold current. The spacer layer is also found to have a beneficial impact on the internal losses (down to 10 cm^{-1}) due to the reduced absorption within the Mg-doped layers [38].

17.2.5 Extending the Wavelength Range of GaN-Based Blue Laser Diodes

Figure 17.1 illustrated the falling luminescence efficiency for LEDs emitting outside of the violet–blue–green spectral range. For LDs, this characteristic of InGaN emitters imposes more severe limitations on the achievable emission wavelengths. Early GaN-based LDs were limited to the 390–420 nm spectral range, which includes the 405 nm selected for next-generation optical discs. However, longer and shorter wavelengths are very desirable, and considerable progress is being made to this end.

17.2.5.1 ‘True Blue’ and Longer Wavelengths

Nichia Corporation has reported results on GaN-based lasers with emission wavelengths ranging from 425 to 454 nm, achieved by changes in the InGaN well-growth temperature [9]. The variation in threshold current is reproduced in Figure 17.13 and highlights the problems to be overcome in raising the lasing wavelength. At this time, cw lasing was not achieved above 455 nm, due to the reduced quality of the layers with a higher indium nitride fraction and the damaging effects of band-tail states.

Spectra for LDs emitting at 402, 422 and 447 nm are illustrated in Figure 17.14 as a function of excitation current density [32]. The 402 nm laser shows a red-shifting peak (~5 nm) due to heat generation. However, the 422 and 447 nm samples both show a blue shift (~10 and 15 nm), attributed to screening of the in-built piezoelectric fields for current densities below 0.25 kA cm^{-2} and thereafter dominated by the band-tail filling. Ref. [32] also shows microscope images revealing deterioration of the quality of the ELOG material as the wavelength increases from 440 to 460 nm, which may be related to dissociation of the InGaN during growth of the p-type cladding layers.

Despite the difficulties, progress has been steady and the Nichia Corporation has been offering a commercial LD emitting at a wavelength of 440 nm for some time. The specifications are not dissimilar to those of the commercial 405 nm 5 mW LD, although the typical operating voltage and current are increased to 5 V and 55 mA, respectively [31].

By mid-2001, Nichia had published details of InGaN LDs with emission wavelengths in excess of 460 nm [39]. The room-temperature threshold current density of the device emitting at 460 nm was 3.3 kA cm^{-2} and the estimated lifetime approximately 3000 h. The improvement in material quality using the ‘ELOG on GaN’ substrates described earlier has proved significant for enhancing the performance of the longer-wavelength GaN-based LDs [32]. The Nichia Corporation achieved GaN-based room-temperature cw lasing at 488 nm, and further extensions of wavelength are sure to follow, albeit with declining performance characteristics [40].
17.2.6 Mode Structure and Control

Early GaN lasers with ridge widths above 3 μm gave outputs with multiple transverse modes for moderate powers. These are highly undesirable for optical storage and high-resolution spectroscopic applications but by narrowing the ridge widths, Nakamura achieved lasers with only the fundamental transverse mode for variable operating current [43].

When increasing the power of GaN-based lasers, kinks are sometimes seen in the L–I traces, which are generally associated with a change in the transverse mode structure. ‘Kink-free’ operation has been demonstrated for powers in excess of 100 mW by suppression of higher transverse modes. For example, the conventional ridge structure has been replaced with one including layers of silicon or ‘spin-on-glass’ that preferentially absorb the first mode [37,38].

Similar suppression of higher modes can be achieved by fabrication of distributed feedback (DFB) gratings, as described in Refs. [44] and [45]. Such gratings are defined by periodic variations in the refractive index, such as by etching trenches, laterally coupled to the optically active region. This also enables the emission wavelength to be tuned across the gain spectrum. For example, the use of DFB gratings with periods between 160 and 170 nm results in a 10 nm tuning range for a ~400-nm GaN-based LD, with single-mode behaviour [44].

17.3 Stimulated Emission Mechanisms in GaN and Related Materials

As previously mentioned, the remarkable luminescence efficiency of the dislocation-ridden InGaN LEDs appears to be related to the spontaneous formation of strongly localizing In-rich regions [13–15,33]. These regions result from segregation of InN and GaN and have a quantum-dot-like nature, which concentrates excitonic recombination away from the non-radiative centres. Strong strain variations and intense piezoelectric fields are associated with these composition variations and have major effects on the characteristics of the luminescence. However, many or all of the localized states will be filled in the stimulated emission (SE) regime controlling the operation of the LDs and different mechanisms will become dominant.

17.3.1 Stimulated Emission in GaN

SE from GaN was first reported as early as 1971 by Dingle et al. [46], using single-crystal GaN needles at 2 K. Later studies have demonstrated SE in GaN at temperatures up to 700 K [47]. The large excitonic binding energy in GaN means that exciton effects persist to high temperatures as can be observed, for example, in measurements of optical absorption at elevated temperatures [48]. SE, however, involves much higher excitation densities than in these demonstrations and the contribution of excitons will depend on the degree of screening of the Coulomb interaction by the carriers. Bidnyk et al. [49] reported a temperature dependence (20–700 K) of the SE threshold in GaN epilayers grown on sapphire and SiC substrates. Figure 17.15 shows the measured SE threshold.
and the availability of more closely matched substrates will be available. For example, homoepitaxy is possible using ZnO substrates \([54]\) and ScAlMgO\(_4\) substrates are almost lattice-matched to ZnO \([55]\). ZnO is naturally n-type but, as in the development of GaN devices, progress towards ZnO-based light emitters has been held up by the difficulty of doping p-type materials. However, Eagle Picher Technologies have demonstrated p-ZnO layers doped with Mg giving carrier densities of \(~10^{19}\,\text{cm}^{-3}\) (although at very low mobility) \([54]\). Given the advantages listed here, further progress with p-type ZnO could be expected to result in the emergence of high-performance LEDs and, possibly, lasers. Nevertheless, it remains to be seen whether the spontaneous segregation and large polarization fields within the III-nitrides are the key to success in these areas.

### 17.4 Non-GaN Blue Lasers

#### 17.4.1 ZnO

ZnO is a wide bandgap \((E_g = 3.37\,\text{eV} \text{ at } 300\,\text{K})\) semiconductor with similarities to GaN (e.g. wurtzite structure) but also a number of potential advantages. These include the extremely large excitonic binding energy (at ~60 meV, considerably larger even than for GaN); there is the possibility that lattice-matched heterostructures using Mg\(_{x}\)Zn\(_{1-x}\)\text{Cd}_{0.2}\text{O} \text{ compounds and the availability of more closely matched substrates will be available. For example, homoepitaxy is possible using ZnO substrates [54] and ScAlMgO}_4 substrates are almost lattice-matched to ZnO [55]. ZnO is naturally n-type but, as in the development of GaN devices, progress towards ZnO-based light emitters has been held up by the difficulty of doping p-type materials. However, Eagle Picher Technologies have demonstrated p-ZnO layers doped with Mg giving carrier densities of ~10^{19}\text{cm}^{-3}\) (although at very low mobility) [54]. Given the advantages listed here, further progress with p-type ZnO could be expected to result in the emergence of high-performance LEDs and, possibly, lasers. Nevertheless, it remains to be seen whether the spontaneous segregation and large polarization fields within the III-nitrides are the key to success in these areas.

#### 17.4.2 Frequency Doubling

An alternative approach to semiconductor-based blue lasers involves frequency doubling of high-power infrared diodes. Both Matsushita and Coherent have second harmonic generation (SHG) blue lasers emitting 20–30 mW. Matsushita has demonstrated a 31% power conversion efficiency using SHG in a periodically poled MgO:LiNbO\(_3\) waveguide by frequency doubling an AlGaAs LD [56] and has a 410-nm emitter suitable for writing to optical discs. Coherent’s devices employ an 810-nm diode to optically pump a vertical external cavity surface emitting GaAs-based laser and use different gain regions for devices emitting at 460 and 488 nm.

The size of the resulting device is an issue but Matsushita has reduced the package for their SHG laser to an impressive 0.3 cm\(^3\), which may be suitable for optical disc writers [57].

#### 17.4.3 II–VI Materials

ZnSe-based blue lasers have been demonstrated with room temperature lasing at 463 nm (pulsed mode, binary ZnSe quantum well [58]) and 490 nm (cw mode, CdZnSe quantum well [59]). A major obstacle to the development of II–VI lasers remains the limited lifetime, largely resulting from the formation of dislocation networks in the active region, and the significantly higher lifetimes demonstrated for GaN-based lasers mean that ZnSe-based structures are very unlikely to compete in the blue region. However, as discussed in Section 6.5 the II–VI lasers retain pole position for diode lasing at wavelengths above 500 nm, where InGaN proves more problematic.

#### 17.5 Extension of Lasing Emission beyond the Blue/UV, Green and Yellow Laser Diodes

As described in Section 6.2.5, the longest lasing wavelength demonstrated for GaN-based LDs is currently 488 nm. Researchers on III-nitride lasers will continue to work on increasing this value, but experience thus far indicates that progress will be hard won. Thus far, diode lasers operating in the 510–520 nm green spectral region have only been demonstrated in ZnSe-based devices, including CdZnSe quantum
wells. For these devices, optimization of the point defect density within the active layer enabled researchers at Sony to report a ~400h cw lifetime at 20°C in 1998 [60], although that result still retains the record for longevity.

Conventionally, ZnSe-based LDs are grown on conductive (n-type) GaAs substrates allowing back contacting [60,61]. The active region is composed of CdZnSe or CdZnSSe quantum well(s), typically 3–4 nm wide. A separate confinement structure is employed using MgZnSSe cladding layers and ZnSSe waveguiding layers. The p-type contact can be formed by a ZnTe/ZnSe multi-quantum-well structure although there are other schemes with potential advantages. Indeed, achieving a reliable low-voltage ohmic p-contact remains one of the challenges for ZnSe-based lasers and appears to limit the lifetime [62]. The degradation of II–VI LDs is mostly due to a gradual worsening of lifetime, catastrophic optical damage has been observed.

As mentioned earlier ZnSe-based lasers are unable to compete with the III-nitrides for blue emission but are currently superior in the green/yellow area. Careful optimization of CdZnSSe quantum wells has led to the demonstration of yellow laser emission (560 nm) [63]). The increased Cd content of the wells required for such emission tends to lead to high strains when using GaAs substrates, which would be expected to impair lasing severely. The addition of S to give the quaternary wells has allowed high structural and optical quality to persist even with Cd contents of up to >40% [63]. In some respects, the characteristics (e.g. higher resistance to catastrophic optical damage with 560 nm, powers exceeding 1 W in pulsed mode) of the yellow lasers exceeds that of the shorter-wavelength ZnSe-based structures. This reflects the improved carrier confinement at the longer wavelengths since the bandgap of the MgZnSSe cladding material is similar in both cases.

The development of ZnSe substrates offers an alternative homoepitaxial route to ZnSe-based diode lasers with a number of potential advantages, including reduced defect densities and absorption losses. Very low thresholds (current densities as low as 176 A cm⁻² [64]) have been demonstrated for II–VI gain-guided LDs on ZnSe substrates and attributed to the reduction in the internal losses occurring in a non-transparent substrate such as GaAs. However, Wenisch et al. [65] describe a comparison of the characteristics of devices grown on GaAs and ZnSe substrates and report some similarities in the propagation of defects, although they have a relatively high defect density in the homoepitaxial lasers.

### 17.6 Conclusion and Outlook

The rapid development of III-nitride semiconductor devices in the past decade has produced high-performance LDs covering the UV to blue/green spectral region with more than 30 mW available in commercial 400–420 nm emitting devices. The rate of progress remains high, both in increasing power and extending the wavelength range. Schemes to minimize dislocations have been shown to be important in all of the GaN-based LDs. The most attractive of these would be the use of true bulk GaN substrates, for which the demonstration of lasers has been described. The difficulty of producing such GaN substrates remains extremely hard, however. ZnO-based devices may yet compete with the III-nitrides for blue LDs, with the availability of matched substrates a considerable advantage, but the development is at a very early stage. LDs based on the II–VI LDs will almost certainly not be able to compete in the blue spectral region, but they still hold the ground for use in green/yellow LDs. It remains to be seen whether the success of the III-nitrides in the UV and blue can be extended into these longer wavelength regions.

### REFERENCES